BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B71 02031

SUBJECT: Earth Orbit Payload Capabilities of the Saturn IB and CSM for Altitudes Up to 1000 nm and Inclinations Up to 100 Degrees - Case 610

DATE: February 16, 1971

FROM: P. H. Whipple

ABSTRACT

Payload capability data are graphically presented for the Saturn IB and CSM for a wide range of altitudes and inclinations. Three different launch profiles were considered:

1. Saturn IB launch of a CSM into an 81 x 120 nm insertion orbit with subsequent CSM Hohmann transfer maneuvers to a final circular orbit,

2. Same as (1), but with a propulsive assist from the CSM during the ascent to the 81 x 120 nm insertion orbit (2-1/2 stages-to-orbit launch), and

3. Direct launch by the Saturn IB to a final circular orbit.

The altitudes varied from 120 to 1000 nm for launch profiles 1 and 2, and from 100 to 300 nm for launch profile 3. The orbital inclination varied from 28.4 to 100 degrees for all profiles. The first two launch profiles are representative of manned launches and the third launch profile is representative of an unmanned launch. All launches were in-plane launches from KSC.

For the manned launch profiles, payload capability data with the SPS and RCS deorbit propellants excluded is also presented graphically.

Payload can be computed from a simple second-order algebraic formula, expressing payload as a function of altitude and inclination, with an accuracy of better than 200 lbs over a range of inclinations from 28.4 to 100 degrees, and a range of altitudes of 120 to 1000 nm for launch profiles 1 and 2 and 100 to 300 nm for launch profile 3. Values for all necessary constants for this computation for each launch profile are given. Payload tradeoff factors relating increments in payload weight to increments in inclination and altitude can also be easily computed and are given for each launch profile.

(NASA-CR-116595) EARTH ORBIT PAYLOAD CAPABILITIES OF THE SATURN IB AND CSM FOR ALTITUDES UP TO 1000 NM AND INCLINATIONS UP TO 100 DEGREES (Bellcomm, Inc.) 25 p

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MEMORANDUM FOR FILE

I. Introduction

Fundamental to any mission planning activity is the payload capability of the launch vehicle. Previous payload studies for the Saturn IB launch vehicle have usually considered only a limited range of orbital altitudes and inclinations, and only the payload placed into the initial insertion orbit. It is often necessary to consider cases with less restrictive conditions. The payload delivered to a final circular orbit may be of more interest than that placed in the initial insertion orbit. Also, payloads for a wide range of orbital inclinations and altitudes may be of interest when considering the feasibility of very high inclination missions, such as those with sun-synchronous orbits, or for possible participation in international space efforts that may be conducted at high inclinations and/or high altitudes.

This memorandum presents the payload capabilities for three Saturn IB launch profiles:

1. Saturn IB launch of a manned CSM spacecraft into an 81 x 120 nm initial insertion orbit with subsequent CSM Hohmann transfer maneuvers to a final circular orbit,

2. Same as (1), but with a propulsive assist from the CSM during the ascent to the 81 x 120 insertion orbit (commonly called a 2-1/2 stages-to-orbit launch), and

3. Saturn IB unmanned direct launch to a circular orbit.

The first two launch profiles are referred to as manned launches as a notational convenience to identify the availability of CSM propulsion and the presence of a Launch Escape System (LES) and a Spacecraft Adapter (SLA) during the appropriate portions of the ascent. The third launch profile presumes the payload to be passive during the ascent to orbit, and is referred to as unmanned to imply the absence of an LES.

The results of this study are given in Section II. A discussion of the computer simulations used to generate the payload curves and of a simple, accurate analytic method of computing payload are given in Section III.

II. Summary of Results

Payload capability data are necessarily best presented in graph form and the results of this investigation are presented in Figures 1 through 6. However, selected examples of these data are given below in Table 1 for manned CSM spacecraft.

TABLE 1

CSM SPACECRAFT WEIGHT IN ORBIT, LBS.

i	h	Saturn IB to 81x120, CSM to final circular orbit	Saturn IB + CSM to 81x120, CSM to final circular orbit
28.4	235	33900	36700
	500	31200	33700
	1000	27100	29300
50	235	31600	34700
	500	29100	31800
	1000	25200	27700
65	235	29600	32900
	500	27200	30300
Sun-Synchronous	235	25100	29100

These weights are total spacecraft weights placed in the final circular orbit and do not include weights of items disposed of prior to final orbit insertion such as the Launch Escape System (LES) and the Spacecraft Adapter (SLA).

In all cases a significant gain in payload is realized by using the CSM to assist in the ascent to the insertion orbit. For low altitude - low inclination orbits, this gain is about 3000 lbs. For a fixed altitude, this gain increases with increasing inclination. For a fixed inclination, this gain decreases with increasing altitude.

Shown in Figures 1 and 2 are the total spacecraft weights placed in orbit for these two launch profiles, for inclinations from 28.4 to 100 degrees and for altitudes from 120 to 1000 nm. Shown in Figures 3 and 4 are the corresponding "dry" spacecraft weights, i.e., with the deorbit propellants excluded. Figure 5 relates deorbited dry spacecraft weight to total spacecraft weight just prior to the deorbit maneuver, and hence to the required deorbit propellants, and can be useful for cases where sizable weight changes occur in orbit between insertion and deorbit. It is assumed that primary (SPS) and backup (RCS) deorbit capabilities are both required. The data given in Figure 5 are independent of inclination and mode of ascent to orbit.

Shown in Table 2 below are examples of payload data taken from Figure 6 for a Saturn IB unmanned direct launch into circular orbit. These payload weights are exclusive of the S-IVB stage and its contents, but do include the weight of any payload shroud or spacecraft adapter weight that is present. These payload weights correspond to what is sometimes referred to as weight mounted above the Instrument Unit (IU) of the launch vehicle.

TABLE 2

SATURN IB UNMANNED PAYLOAD WEIGHTS - DIRECT LAUNCH

i	h	Payload Weights, lbs.
28.4	200	33300
	300	24200
50	200	31300
	300	22500
65	200	29500
	300	21100
Sun-Synchronous	200	25400

Although the data of Figures 1 through 6 were generated with computer simulations, the payload weight can be analytically computed with an accuracy of better than 200 lbs from a polynomial expression for any of the three launch profiles considered in this memorandum. This expression is

$$P = C_1h^2 + C_2i^2 + C_3ih + C_4h + C_5i + C_6 \quad ,$$

where h is the altitude in nm, i is the inclination in degrees, P is the payload weight in lbs, and the C's are constants.

Each launch profile has its unique set of values for the constants, which are given in Table 3.

TABLE 3

COEFFICIENTS FOR ANALYTIC PAYLOAD COMPUTATION

	Saturn IB to 81x120, CSM to final circular orbit	Saturn IB + CSM to 81x120, CSM to final circular orbit	Unmanned Saturn IB to circular orbits
C_1	.002745	.003069	-.09675
C_2	-.3026	-.2111	-.34442
C_3	.03673	.03227	.19115
C_4	-13.451	-14.469	-47.996
C_5	-102.51	-94.245	-110.71
C_6	40007.	42715.	49186.

Payload computations performed in this way are valid to the above stated accuracy over a range in inclinations from 28.4 to 100 degrees, and over a range in altitudes from 120 to 1000 nm for manned indirect launches and 100 to 300 nm for unmanned direct launches.

Payload tradeoff factors relating increments of payload weight to increments in altitude and inclination are easily computed from the above expression and are given in Figures 7, 8, and 9 for the three launch profiles.

III. Discussion

A. Generation of the Payload Curves

The curves of payload capability for each of the launch profiles were generated by simulating the launch into the insertion orbit with computer runs made with the Bellcomm Apollo Simulation Program (BCMASP). For launches into the

81 x 120 insertion orbit, Hohmann transfer maneuvers were used to transfer from the insertion orbit to the final circular orbit and were computed assuming instantaneous burns. In all cases, northerly in-plane launches from Cape Kennedy were used. It was found that southerly launches result in slightly greater payloads, but these differences were small, varying from 0 to 280 lbs over an inclination range of 28.4 to 90 degrees for the 81 x 120 insertion orbit.

For the computation of deorbit propellant, a retrograde tangential deorbit burn into an orbit with a perigee radius equal to the radius of the earth was assumed. While this assumption is an approximation to actual practice, it should not introduce much error in the computation of deorbit propellant required. For the SL-3 mission, deorbit propellants computed in this way only differ by 177 lbs, or seven percent, from those given in Reference 1.

The launch vehicle characteristics used in the computer simulations are those for the AS-207 vehicle that will be used for the SL-3 mission. The vehicle weight data are shown in Table 4 and taken from Reference 2 with the following exceptions. The Launch Escape System (LES) weight and the S-IVB Flight Performance Reserve (FPR) were taken as those values being used for the SL-3 mission as given in Reference 3. This FPR weight is 2000 lbs, 500 lbs greater than that used in Reference 2. For the manned launches into the 81 x 120 insertion orbit, a Spacecraft Adapter (SLA) weight of 4091 lbs, from Reference 3, was jettisoned just prior to the first CSM burn. In all cases the payload weights were adjusted to achieve complete consumption of the launch vehicle propellants, except for the FPR. For 2-1/2 stages-to-orbit launches, the CSM propellant consumed was varied to produce the maximum payload into the insertion orbit.

The propulsive characteristics are shown in Table 5 and taken from References 2 and 4. The aerodynamic characteristics of the manned launch vehicle are given in Figure 10 and taken from Reference 2. The aerodynamic characteristics of the unmanned launch vehicle are shown in Figure 11 and taken from Reference 5. The data for the unmanned vehicle assume the use of the payload shroud that was to have been used with the launch of the wet workshop.

The sequence of events for the ascent to insertion orbit is shown in Table 6 and is taken mostly from Reference 2.

B. Discussion of Results

In an attempt to validate the computer simulation model, a comparison can be made between the control payload capability shown in Reference 3 for the SL-3 mission and the payload obtained in this study for the same inclination and altitude. These payload weights are computed below.

SL-3 Simulation		Reference 3	
Spacecraft Weight	33146	Control Payload Capability	35400
SLA	4091	LV Modifications	440
		Yaw Steering Allowance	700
	37237		36540

These two weights differ by 697 lbs. However, the 35400 lb control weight from Reference 3 is not strictly a payload capability but a minimum acceptable payload capability. Therefore, it is expected that the error is somewhat less than 647 lbs. A similar comparison between the simulator results and the payload inserted into a 29-degree inclination, 81 x 120 nm insertion orbit by the AS-207 launch vehicle as given in Reference 2 shows a difference in payload weight of only about 275 lbs.

In the 2-1/2 stages-to-orbit launch profile, the consumed CSM propellant was varied to result in the maximum spacecraft weight into the insertion orbit. However, near this optimum propellant loading point, the payload is a weak function of the consumed CSM propellant. A decrease in payload of only 10 to 20 lbs is suffered for a decrease of 1000 lbs in CSM propellant consumption from this optimum loading point. The optimum CSM propellant consumption is a function only of the inclination and varies from 15100 to 16650 lbs for inclinations from 28.4 to 100 degrees.

(1) High Inclination Missions

For high inclination missions, e.g., 60 - 70 degrees, significant manned spacecraft weights can be placed into orbit. For a 65-degree, 200 nm circular orbit, a dry CSM spacecraft weight of 27800 lbs can be placed in orbit via an unassisted Saturn IB ascent to the insertion orbit. With a 2-1/2 stages-to-orbit launch, this dry spacecraft weight is increased to 30900 lbs. Allowing for a 700 lb yaw-steering allowance to provide for a launch window, the former is about the same as the planned SL-3 spacecraft orbited dry weight and the latter is approximately 3100 lbs greater. Also, the Saturn IB is capable of launching a passive payload of up to 29400 lbs directly into this orbit. As in Section II, dry spacecraft weight is defined here to exclude only the deorbit propellants.

(2) Sun-Synchronous Orbits

Sun-synchronous orbits are orbits whose orbital precession rate induced by the earth's asphericity is equal to the mean angular motion of the earth about the sun. Thus, the solar illumination characteristics of such orbits remain nearly constant in time. The inclination of a sun-synchronous orbit is dependent upon its altitude and eccentricity, and upon the extent of the earth's asphericity. For the orbits of interest here, these inclinations are between 96 and 98 degrees. While the Saturn IB without a CSM assist during the ascent cannot deliver a large payload to sun-synchronous orbits, the 2-1/2 stages-to-orbit launch mode can result in a dry spacecraft weight of 28400 lbs into a 150 nm circular sun-synchronous orbit. The Saturn IB can launch unmanned payloads of up to 28600 lbs into a 150 nm circular sun-synchronous orbit, and 25400 lbs into a 200 nm orbit.

C. Analytic Computation of Payload

Payloads for launch vehicles have usually been determined by computer simulation, as Figures 1 through 6 were in this study. A preferred procedure would be to compute the payload from a simple algebraic expression relating payload to altitude and inclination. While such an expression is essentially impossible to derive theoretically, the regular, well-behaved character of payload curves in general suggest that such an expression does exist. Furthermore, the shape of payload curves for a constant altitude and for constant inclination indicate that the payload is approximately a second-order function of both of these. Therefore, a logical candidate expression is

$$P = C_1h^2 + C_2i^2 + C_3ih + C_4h + C_5i + C_6 \, , \tag{1}$$

where P is the payload in pounds, h is the altitude in nm, i is the inclination in degrees, and the C's are constants that must be determined. Each different launch profile would have a unique set of values for these constants.

For a particular inclination, i_1, expression (1) reduces to

$$P(i=i_1) = C_1h^2 + (C_4 + C_3i_1)\,h + (C_2i_1^2 + C_5i_1 + C_6) \tag{2}$$

$$= A_1h^2 + A_2h + A_3 \, . \tag{3}$$

Using the results of a few computer simulations for $i=i_1$ and different values of h, the constants A_1, A_2, and A_3 can be determined and the constant C_1 is then known. The A constants are determined with a least squares curve fitting technique. Repeating this process for another inclination, i_2, and combining (3) with its twin for $i=i_2$, the constants C_3 and C_4 are determined. Repeating this two-stage process for constant altitudes h_1 and h_2 and various inclinations, the remaining C constants are determined.

For the launch profile consisting of a Saturn IB launch into an insertion orbit of 81x120 nm with subsequent CSM transfer maneuvers to circular orbits, the above approach was used with inclinations of 28.4 and 100 degrees, and altitudes of 120 and 1000 nm. With the resulting evaluated constants, the payload was computed from (1) for every combination of inclination and altitude for which computer results had been obtained to plot the payload curves of Figure 1. Over a range of altitude from 120 to 1000 nm and a range of inclination from 28.4 to 100 degrees, the payload as computed from (1) never differed by more than 174 lbs from the payload determined by computer results. The same procedure was repeated for the 2-1/2 stages-to-orbit launch mode and Saturn IB direct launch to circular orbit mode with the same results. The constants for these three launch profiles are given in Table 3 of Section II. By using these constants with expression (1), the orbited weight can be computed to an accuracy of better than 200 lbs over a range in inclination from 28.4 to 100 degrees, and an altitude range of 120 to 1000 nm for manned missions and 100 to 300 nm for unmanned direct insertion missions.

Having evaluated the constants of (1), payload tradeoff factors between payload and altitude, and between payload and inclination can be easily evaluated. These are useful in estimating the effect on the orbited payload of changing the altitude or the inclination. These factors can be determined by differentiating (1) as follows.

$$\frac{dP}{dh} = 2C_1h + C_3i + C_4, \text{ lbs/nm}$$

$$\frac{dP}{di} = 2C_2\, i + C_3h + C_5, \text{ lbs/degree.}$$

These tradeoff factors are plotted for each of the launch profiles in Figures 7, 8, and 9. If it were desired to determine the effect on the payload of raising the altitude from 200 to 300 nm at an inclination of 50 degrees, for a manned launch by a Saturn IB into the insertion orbit with subsequent Hohmann transfer maneuvers by the CSM, the payload factor can be taken from Figure 7 for i = 50 degrees and an $h = \frac{1}{2}(200 + 300) = 250$ nm as about -10 lbs/nm. The decrease in payload would then be about 10(100) = 1000 lbs, as can be verified by Figure 1.

P. H. Whipple

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Attachments

References

1. Operational Data Book, MSC-01549, Vol. II, Mission Mass Properties, February 1970.

2. AAP-1 Preliminary Performance Data and Flight Profiles, MSFC R-AERO-DAP-9-68, April 23, 1968.

3. Skylab Weight and Performance Report, SE-016-001-1, October 1970.

4. Operational Data Book, MSC-01549, Vol. III, CSM Performance Data, May 1970.

5. AAP-2 Launch Vehicle Performance Analysis, Chrysler Corporation, TN-AP-68-371, December 31, 1968.

6. Ball, K.J., and Osborne, G.F., Space Vehicle Dynamics, Oxford University Press, 1967.

TABLE 4

VEHICLE WEIGHT DATA

S-IB Jettison Weight		102007
S-IB Stage	94761	
S-IB/S-IVB Interstage	6600	
S-IVB Aft Frame	30	
S-IVB Ullage Ret. Prop.	73	
S-IVB Detonage Pkg.	4	
S-IVB Thrust Buildup	426	
LH_2 In Start Tank	4	
Ullage Rocket Prop.	109	
S-IB Propellant Consumed		886382
S-IB Main Stage	882220	
S-IB Inboard Engine Thrust Decay	2178	
S-IB Outboard Engine Thrust Decay	1984	
Misc. Wgts. Jettisoned 70 sec. After Liftoff		1836
S-IB Frost	1000	
S-IVB Frost	100	
S-IB Seal Purge	5	
S-IB Oronite	26	
S-IB Gear Box Lube	705	
S-IVB Jettison Weight		30525
S-IVB Stage	24325	
Flight Performance Reserve	2000	
Instrument Unit	4200	
S-IVB Propellant Consumed		226184
Ullage Rocket Cases		220
Launch Escape System (manned launches only)		9245
SLA (manned launches only)		4091

TABLE 5

PROPULSION DATA

S-IB	THRUST	1,656,200	lbs
	ISP	262.74	s
S-IVB	THRUST	200,153	lbs
	ISP	429.6	s
	MR	5.0	
	THRUST	224,153	lbs
	ISP	426.1	s
	MR	5.533	
	THRUST	184,153	lbs
	ISP	431.3	s
	MR	4.702	
SM	THRUST	20,500	lbs
	ISP	312	s
RCS	ISP	277.3	s

TABLE 6

SEQUENCE OF EVENTS

Time from Lift-off (sec)	Event
0.0	Lift-off
10.0	Initiate Gravity Turn
70.0	Misc. Weights Dropped
132.116	End Gravity Turn
139.116	S-IB Inboard Engine Cutoff
142.116	S-IB Outboard Engine Cutoff
148.116	S-IVB Ignition, MR=5.0
149.416	S-IVB MR Shift to 5.533
158.116	Jettison Ullage Rocket Cases
178.116	Jettison LES
429.416	S-IVB MR Shift to 4.702
612.759	S-IVB Cutoff
2-1/2 Stages to Orbit	Launch Mode Only
618.759	SM Ignition
Varies with CSM Propellant Consumed*	SM Cutoff

*For a CSM Propellant Consumption of 16000 lbs, SM Cutoff Occurs at 862.271.

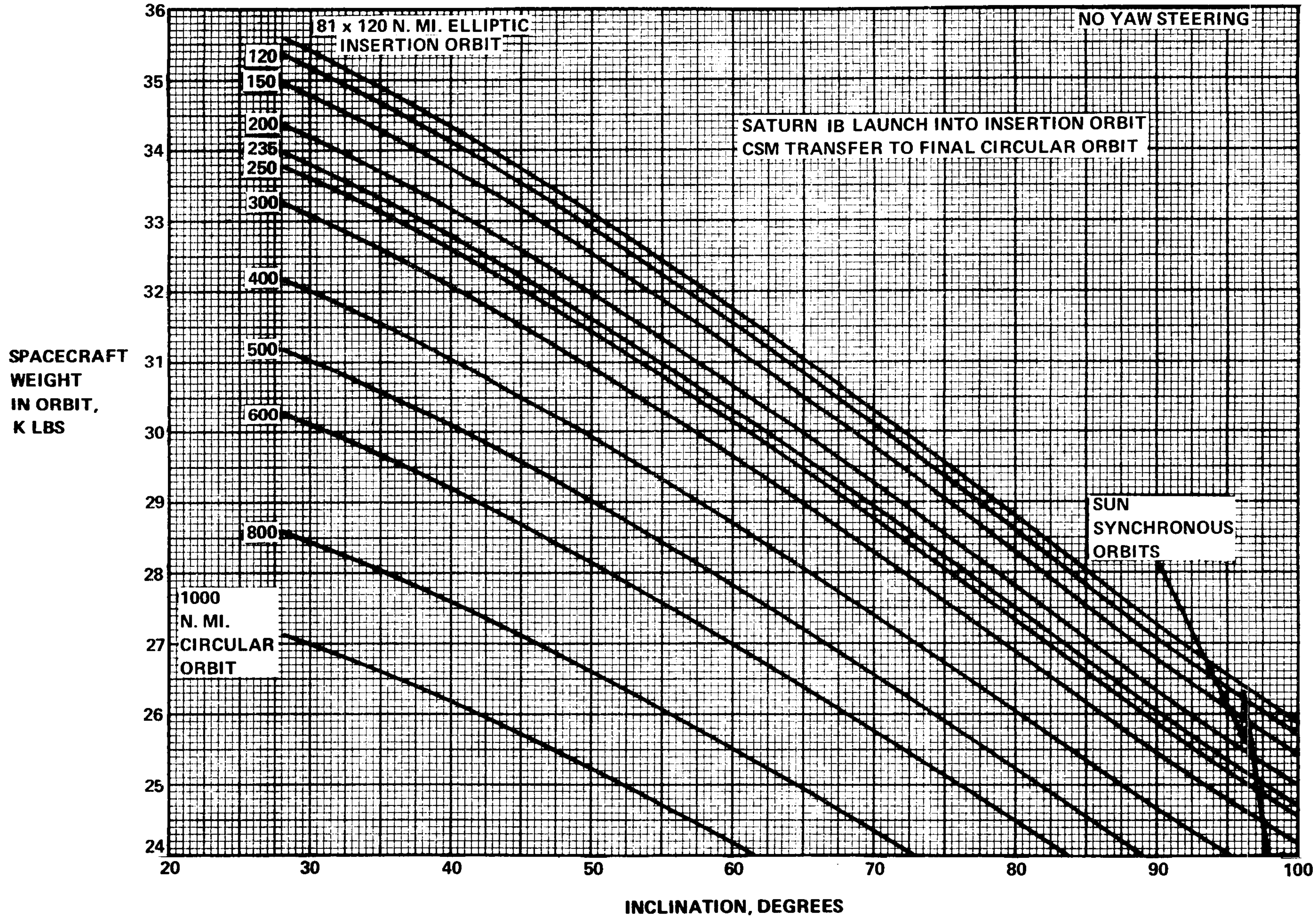

FIGURE 1 - SATURN IB AND CSM PAYLOAD CAPABILITY

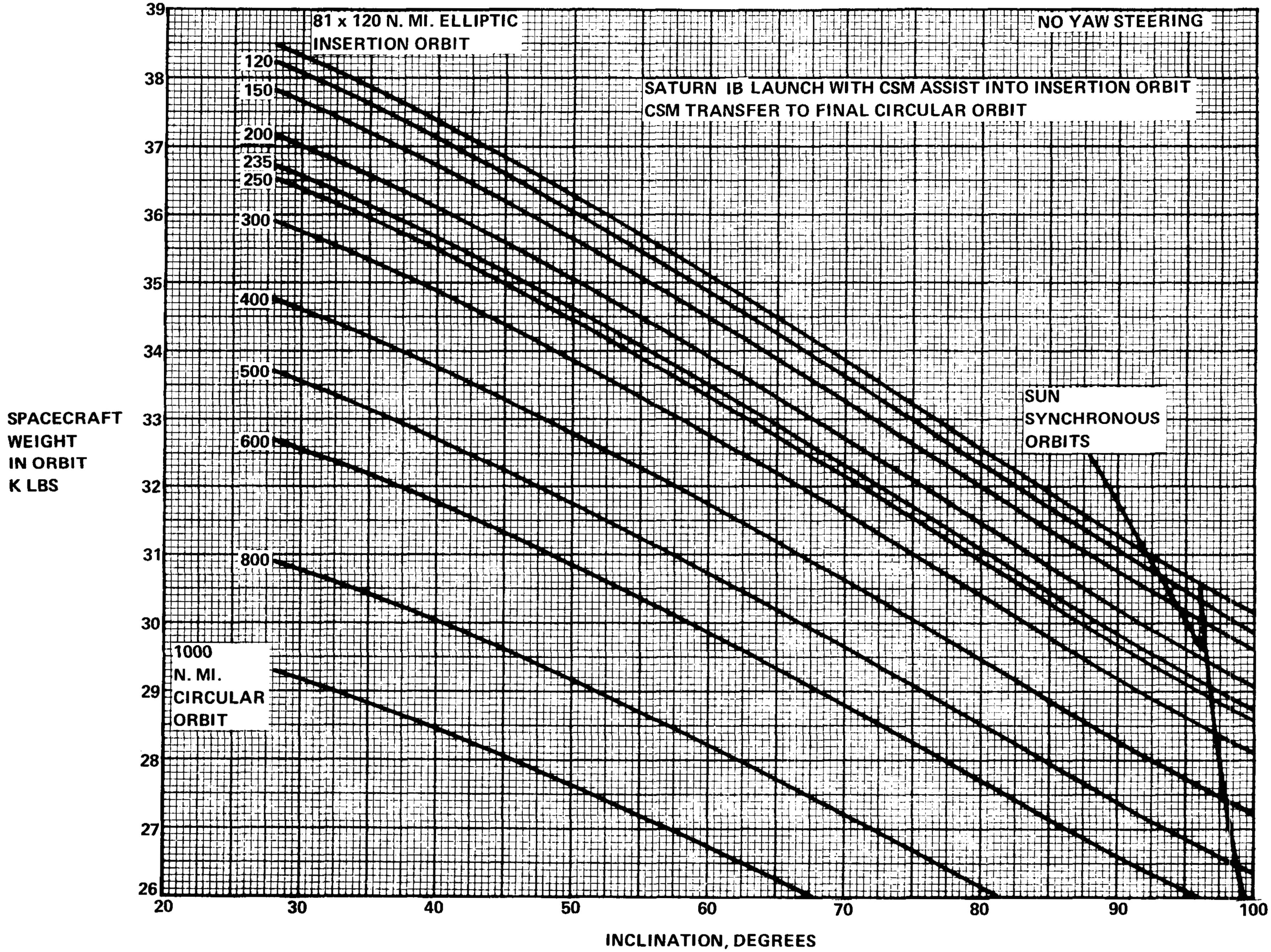

FIGURE 2 - SATURN IB AND CSM PAYLOAD CAPABILITY

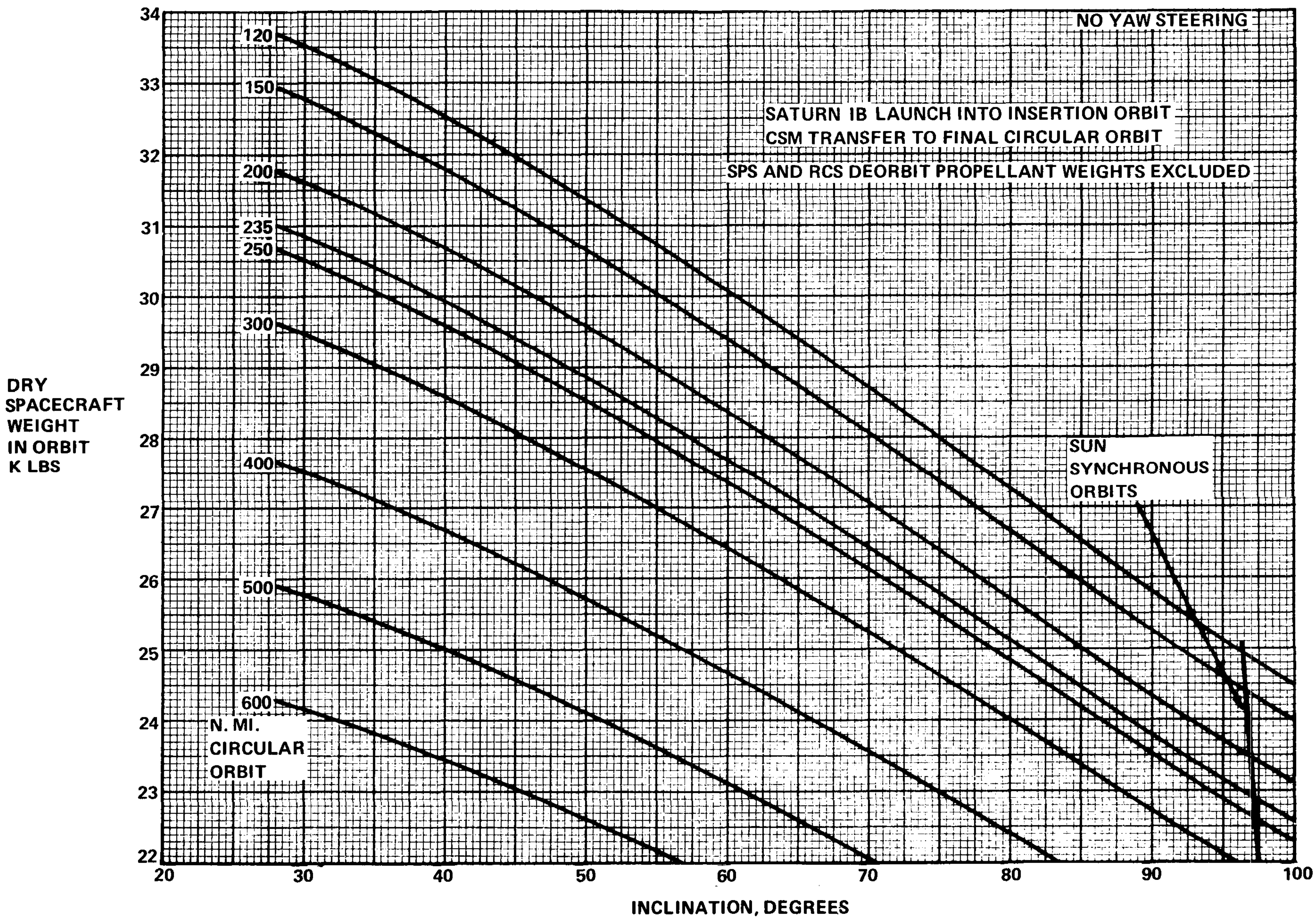

FIGURE 3 - SATURN IB AND CSM PAYLOAD CAPABILITY

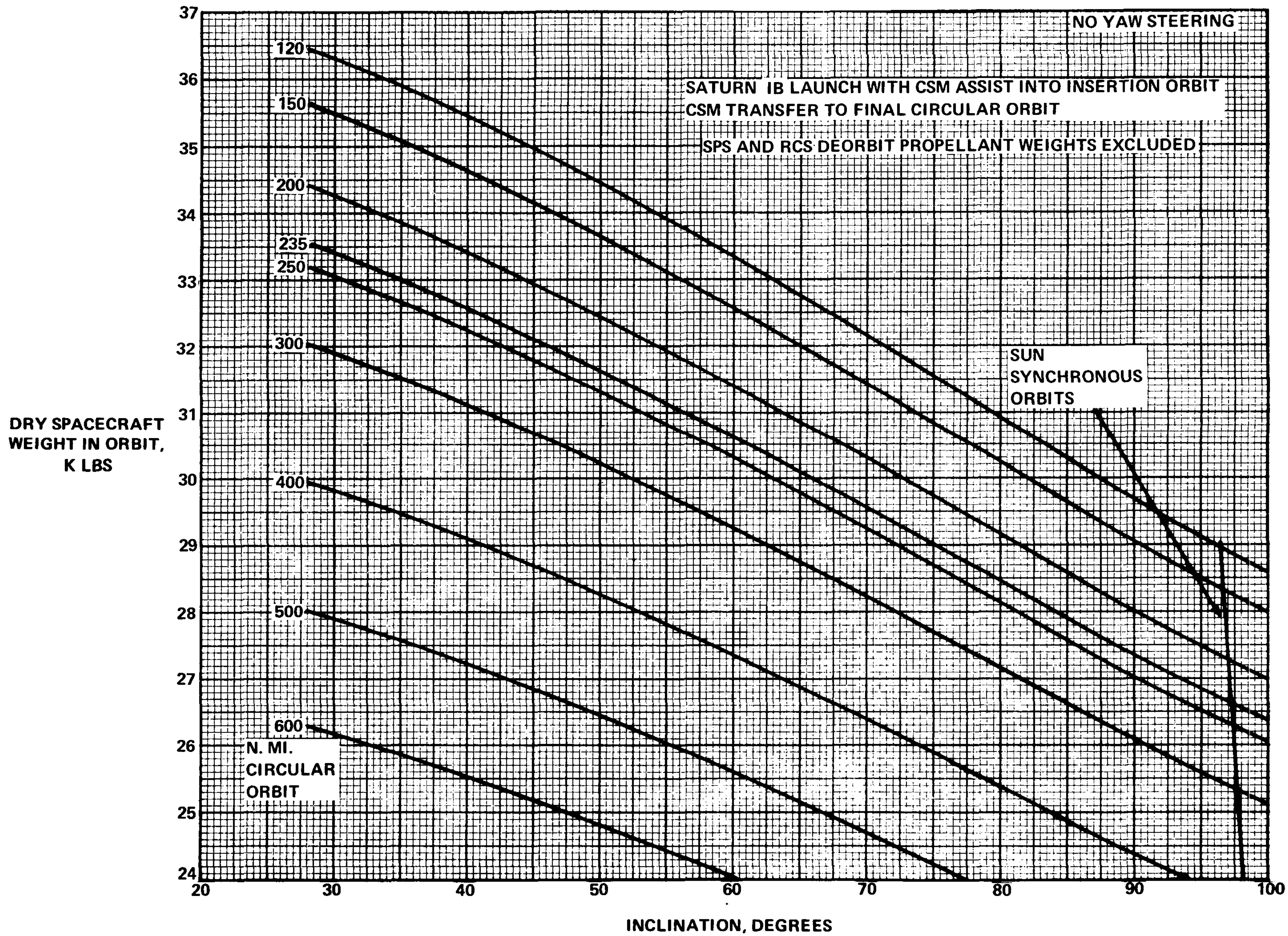

FIGURE 4 - SATURN IB AND CSM PAYLOAD CAPABILITY

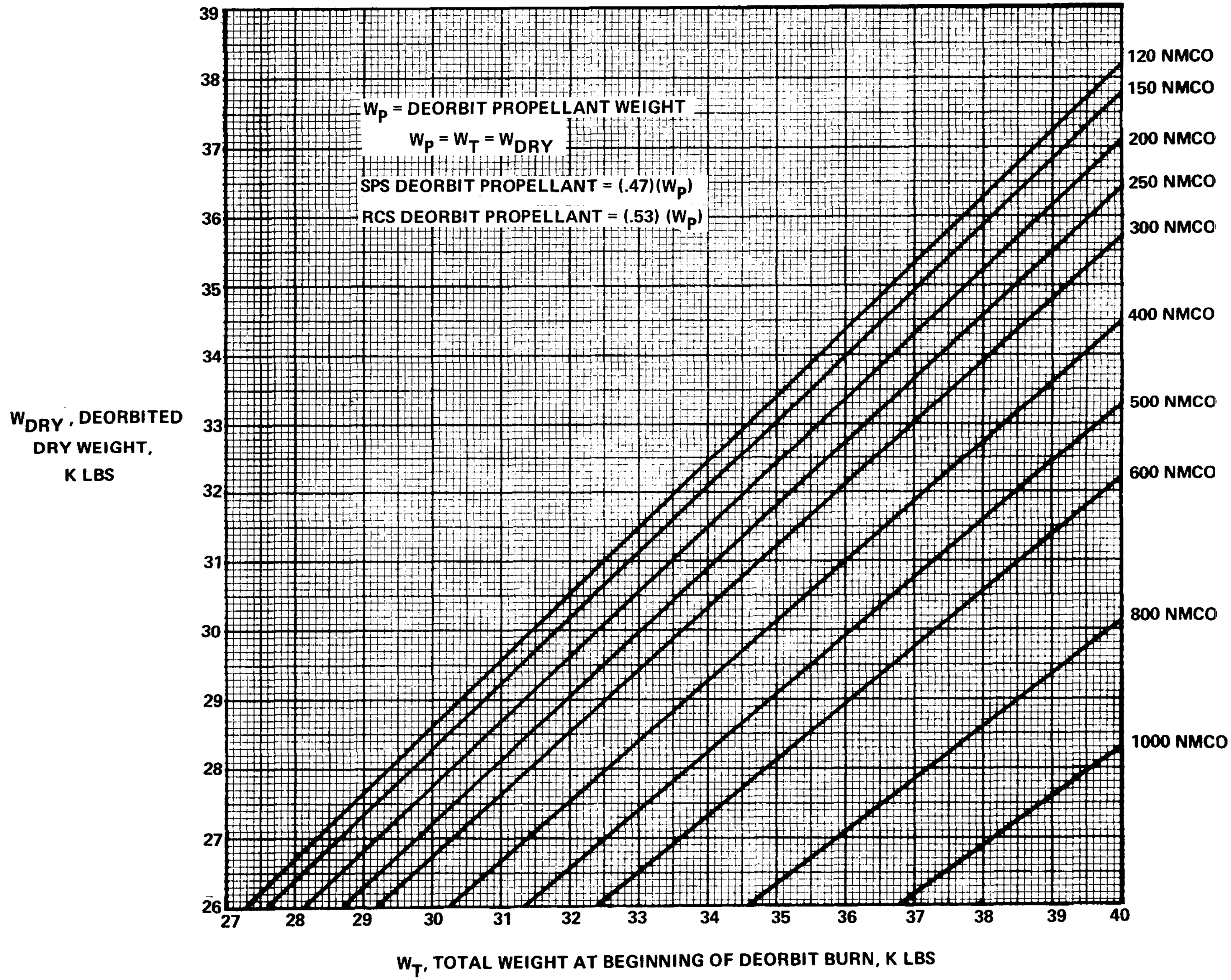

FIGURE 5 - CSM DEORBIT PROPELLANT REQUIREMENTS

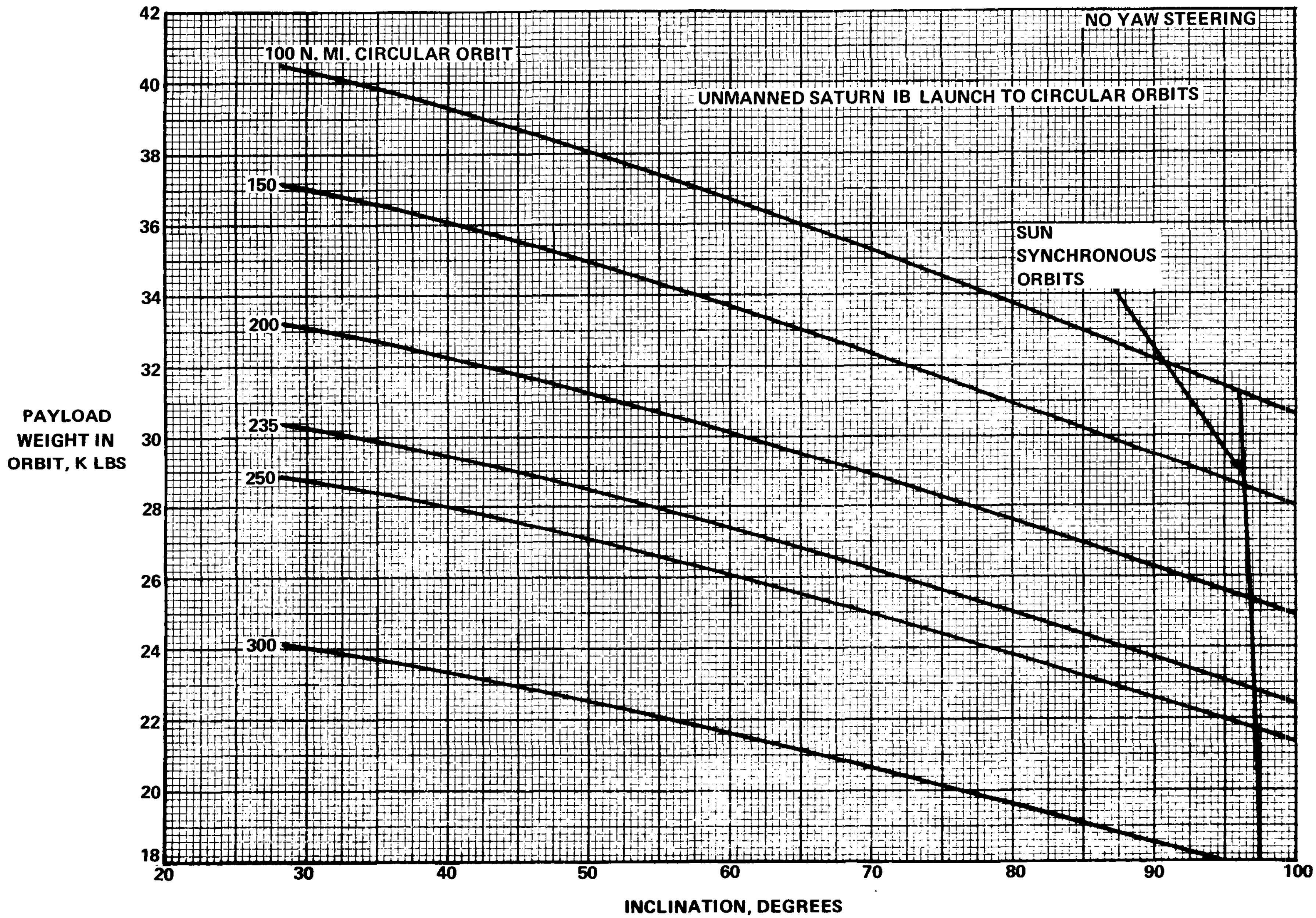

FIGURE 6 - SATURN IB PAYLOAD CAPABILITY

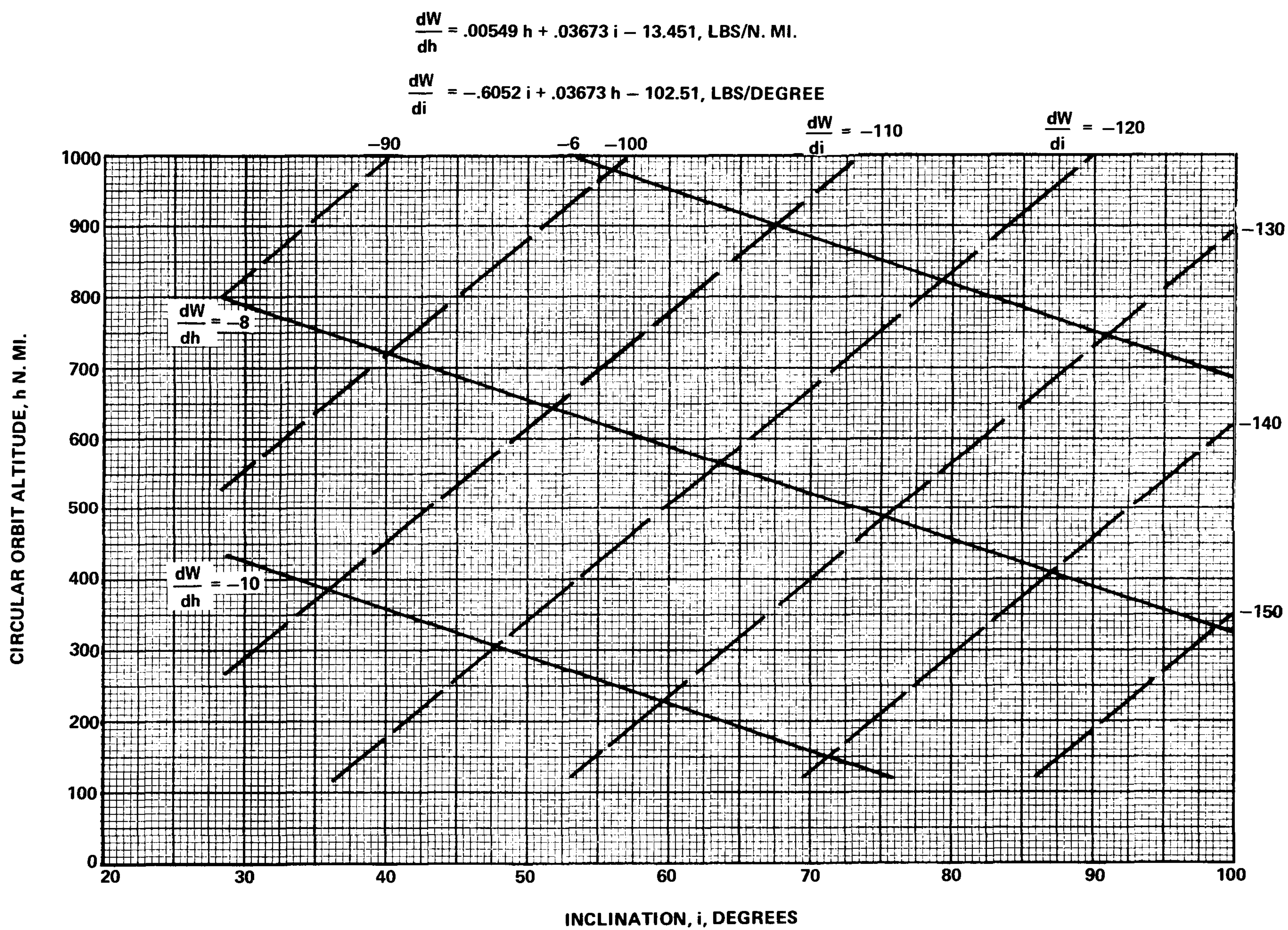

FIGURE 7 - PAYLOAD TRADEOFF FACTORS FOR SATURN IB LAUNCH INTO A 81 x 120 N. MI. INSERTION ORBIT WITH CSM TRANSFER TO CIRCULAR ORBIT

$$\frac{dW}{dh} = .00614\,h + .03227\,i - 14.469, \text{ LBS/N. MI.}$$

$$\frac{dW}{di} = -.4222\,i + .03227\,h - 94.245, \text{ LBS/DEGREE}$$

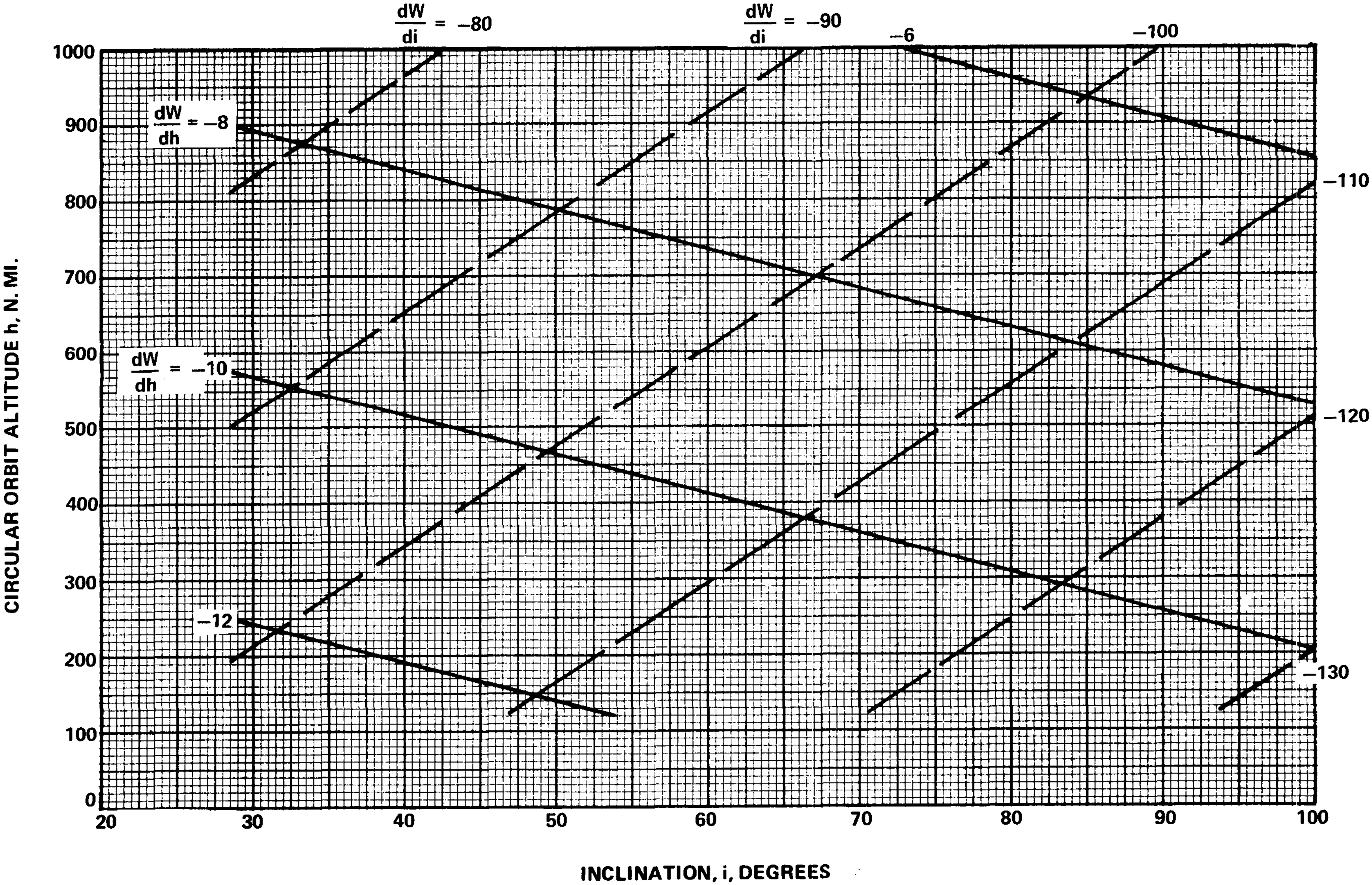

FIGURE 8 - PAYLOAD TRADEOFF FACTORS FOR SATURN IB PLUS CSM LAUNCH INTO A 81 x 120 N. MI. INSERTION ORBIT WITH CSM TRANSFER TO CIRCULAR ORBIT

$$\frac{dW}{dh} = -.1935\,h + .19115\,i - 47.996, \text{ LBS/N. MI.}$$

$$\frac{dW}{di} = -.68884\,i + .19115\,h - 110.71, \text{ LBS/DEGREE}$$

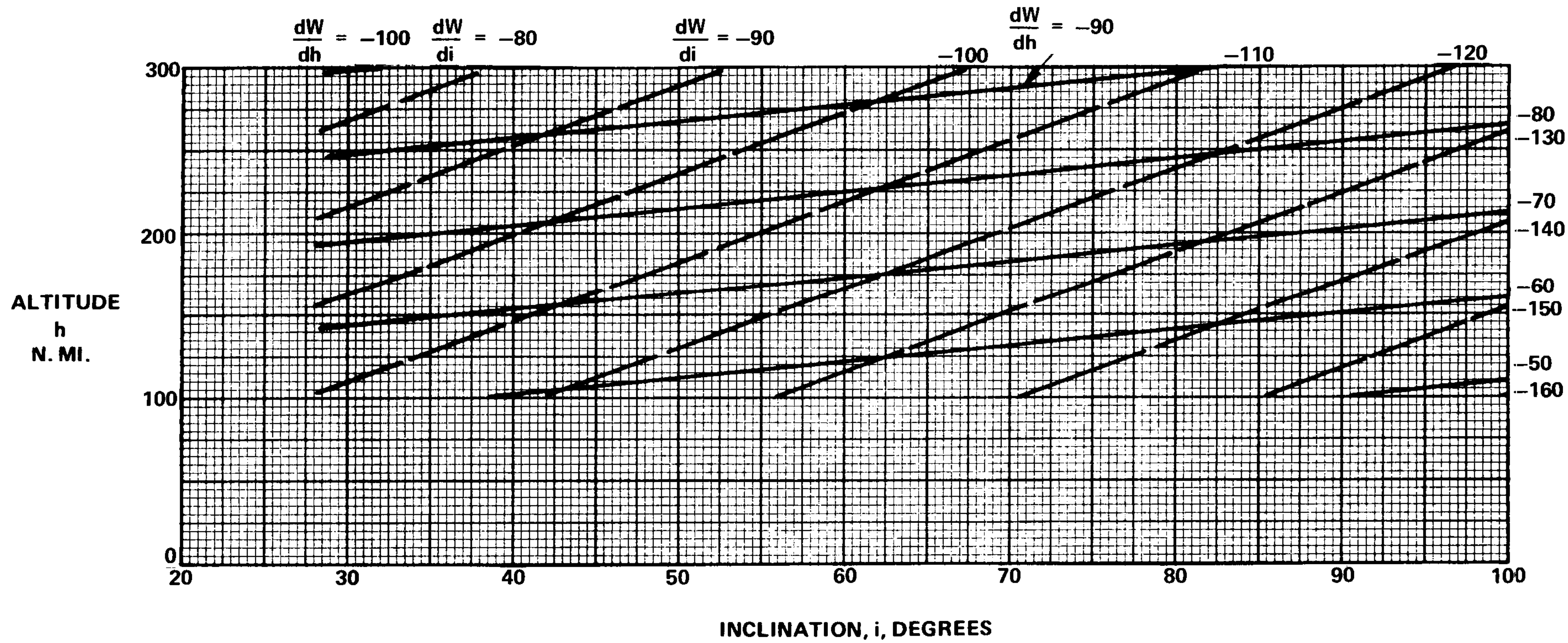

FIGURE 9 - PAYLOAD TRADEOFF FACTORS FOR AN UNMANNED SATURN IB DIRECT LAUNCH TO CIRCULAR ORBIT

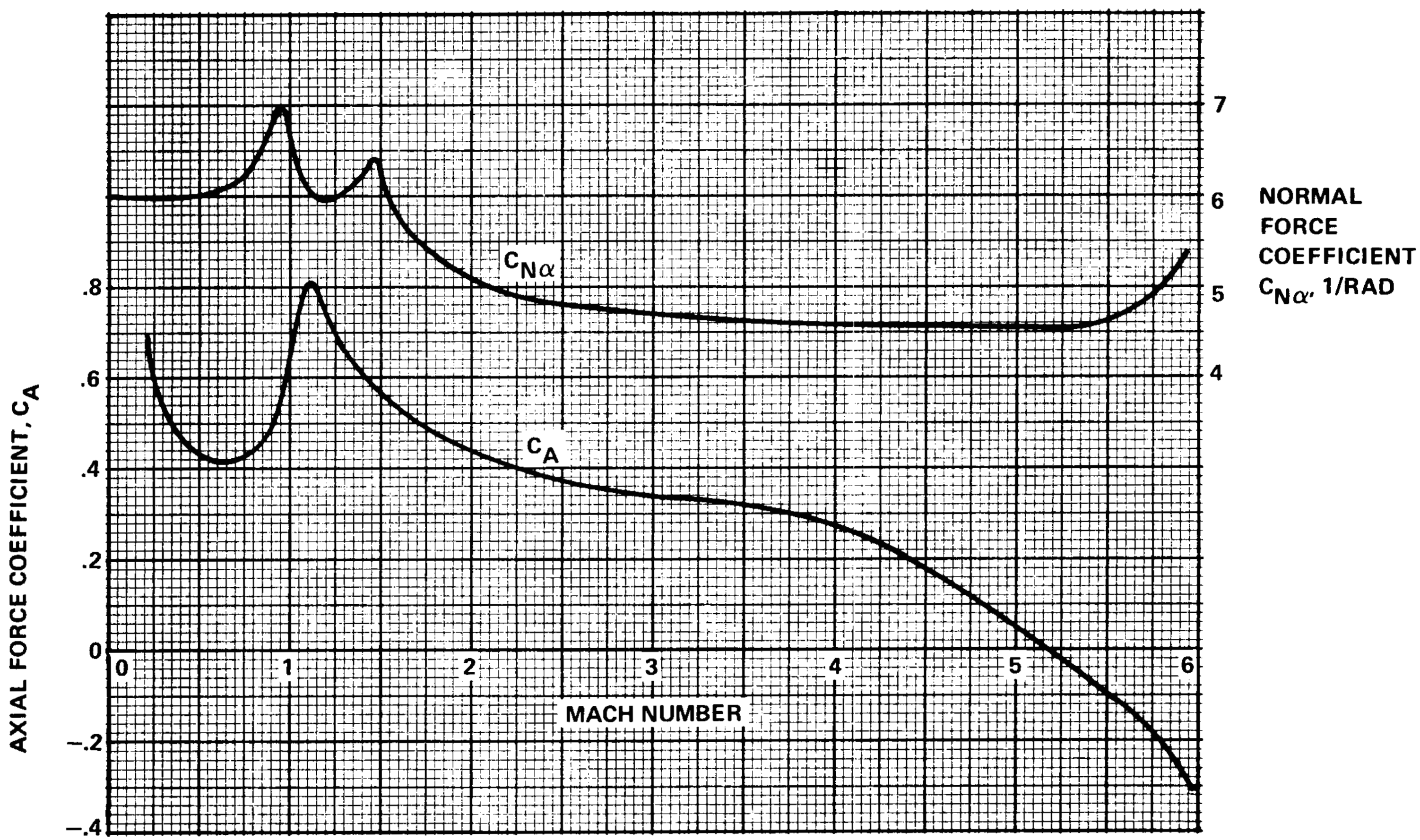

FIGURE 10 - AERODYNAMIC COEFFICIENTS FOR A MANNED SATURN IB SPACE VEHICLE

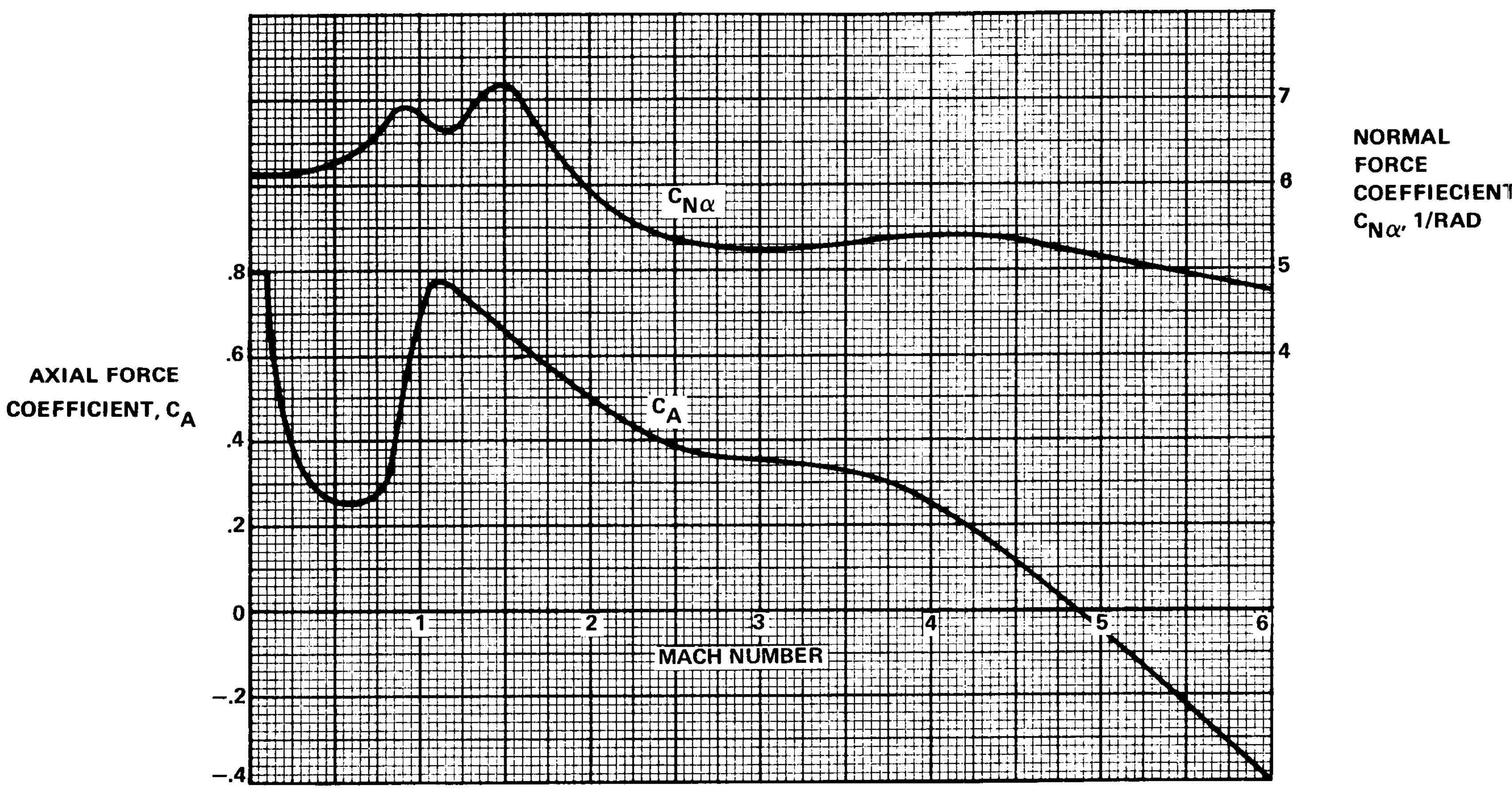

FIGURE 11 - AERODYNAMIC COEFFICIENTS FOR AN UNMANNED SATURN IB SPACE VEHICLE